

DILEPTON PRODUCTION IN ELEMENTARY PROCESSES ON THE NUCLEON *

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Abstract

We study elementary processes for production of dileptons from nucleons, either through NN bremsstrahlung or through photon-induced reactions. We emphasize the dependence of the expected cross-sections on the electromagnetic formfactor of the nucleon in the time-like regime and point out that the mentioned reactions can provide important information on the validity of vector meson dominance for the nucleon. We also study the off-shell dependence of the formfactors.

1 Introduction

Vector meson dominance is a theoretically well developed concept for the description of the coupling between hadrons and photons. While the original idea of Sakurai [1] relied to a large extent on the equality of the quantum numbers of the ρ meson and the photon and the similarity of the Lagrangians describing both particles, the present-day picture is that of charged quark-antiquark loop insertions in the photon propagator which also can change the interaction vertices.

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This picture, appealing as it is, is experimentally well established only for the pion where the measured formfactor shows a clear resonance at the ρ meson mass and can be described by a monopole fit [2]. For other vector mesons and for the nucleon the picture is much less clear. For example, for the nucleon the formfactor in the space-like region exhibits a well-established dipole form, and the time-like region below a momentum of around 2 GeV/c, i.e. the vector meson pole region, is experimentally not accessible [3]. In this paper we argue that the production of dileptons in elementary processes, e.g. in nucleon-nucleon collisions or in photon-nucleon collisions can shed some light on the structure of the electromagnetic formfactor of the nucleon in the time-like region, and thus on the question whether vector meson dominance is a useful concept for the nucleon.

This article is based on 3 very recent publications which contain all the details of the theory and the calculations [4, 5, 6]. The present article therefore summarizes only the main results without going into any of the technical details which can be found in the references just given.

2 Dilepton Bremsstrahlung

Dilepton spectra measured in heavy-ion collisions are dominated by two components, the η Dalitz decay and the $\pi^+\pi^-$ annihilation [7, 8]. Below these two dominant components lies, however, a strong background of dileptons from nucleon-nucleon bremsstrahlung and Δ decay that has a rather strong bombarding energy dependence [7]. In proton reactions on nuclei these two components become dominant for higher invariant masses of the dileptons. It is, therefore, of interest to study these components in a more refined model than the commonly employed long-wavelength approximation.

In [4] we have therefore studied the dilepton production in nucleon-nucleon collisions using an effective T matrix that is based on a One-Boson-Exchange (OBE) model; the T matrix is determined by fitting the nucleon-nucleon elastic scattering. The calculation treats the dilepton emission from nucleon lines and from Δ lines coherently, whereas in standard BUU simulations these two decay channels do not interfere. The interference turns out to be quite important at the higher invariant masses and can describe the observed mass- and bombarding energy dependence of the pd/pp ratio in the dilepton yield (see Fig. 1).

Figure 1: Ratio of dilepton invariant mass spectra for pp to pd at various bombarding energies from 1.03 to 4.90 GeV. The solid dots give the data whereas the line gives results our calculation (from [4]).

Figure 2: Dilepton invariant mass spectrum for $p + {}^9\text{Be}$ at 2.1 GeV. The data are from the DLS group, the lines give results of our calculations: no formfactor (dotted), VMD formfactor for nucleon and Δ (dashed), formfactor from the model of Rho et al [9] (solid) (from [4]).

These calculations were done without any formfactor for the nucleons; under the assumption of universal VMD the formfactors are indeed expected to drop out from the ratio. The absolute cross-sections are, however, very sensitive to the formfactor used. In our calculation we have simply assumed that the electric formfactor has, first, a VMD shape and, second, no off-shell dependence. Under these assumptions the calculations, which are gauge-invariant, give a strong vector meson signal at the ρ meson mass. There are, so far, no published data on dilepton production in pp collisions, but under the assumption that a proton-induced reaction on a light target proceeds mainly through independent pp and pn collisions, the calculations can – properly weighted with the correct number and type of nucleon-nucleon collisions – be compared to the $p + {}^9\text{Be}$ data obtained by the DLS group at Berkeley (see Fig. 2). These data obviously show no special effect in the vector meson mass region.

3 Off-Shell Dependence of the Formfactor

If this result holds up for the $p + p$ data already taken at Berkeley, but not yet publicly available, then there is obviously a gross discrepancy between experiment and data and the question for its reason arises. We have, therefore, studied the electromagnetic formfactor of the nucleon in a model that combines a loop expansion for the π , N and Δ with vector meson dominance for the pion [5]. In this picture the photon couples to the nucleon only through the pion cloud which, in turn, is dominated by VMD in its coupling to the photon. The model allows to study also half-off-shell vertices as they are important in the bremsstrahlungs studies.

The main result of this study, that reproduces the on-shell electromagnetic formfactor of the nucleon in the space-like region quite well, is that the time-like electric formfactor in the particle-particle channel is dominated by VMD, and this VMD is remarkably stable as a function of the off-shellness of the nucleon; the off-shell dependence of the electric formfactor is thus negligible. This is not true, however, for the magnetic formfactor which is strongly off-shell dependent. It is also not true for the antiparticle-particle channel (see Fig. 3) which can play a significant role in bremsstrahlungs processes where – in the so-called post-emission graphs – the nucleon is put off-shell by the NN-interaction before it emits the dilepton; depending on the structure of the T matrix the antiparticle admixture in the virtual nucleon line between interaction and emission can be quite sizeable. It thus seems to be necessary to include these off-shell effects in any analysis of data on $p + p$ dileptons with the aim to determine the formfactor, since for reactions in the GeV bombarding energy range the nucleon can easily go off-shell by several hundred MeV.

4 Compton Scattering into the Timelike Region

The off-shellness of the nucleon in nucleon-nucleon collisions is governed by the strong interaction T matrix, so that the dilepton data are due to an interplay of strong and electromagnetic vertices. This makes it difficult to extract the information on the electromagnetic vertex in an unique way.

A “cleaner” experiment is the photon-induced dilepton production $\gamma +$

Figure 3: Electric formfactors for the proton for various off-shell energies, denoted by the invariant mass W , of the incoming proton (from [5]).

$p \longrightarrow p + e^+e^-$ that – at least in the s and u channels – is free of any strong interaction vertex. The t channel, which involves a photon-photon-meson vertex and a meson-nucleon vertex, does contribute, but only at forward angles between the incoming and outgoing photon because of the low mass of the intermediate virtual pion (in this energy range there are no other physical mesons with an appreciable photon-vector meson coupling strength). As we will see below the forward direction is, however, unsuitable for any dilepton production experiments, because here the (in this context uninteresting) Bethe-Heitler contribution dominates. This may be different if one is interested only in total cross sections for the photoproduction of vector mesons [10]; if these are identified by hadronic decay channels then the Bethe-Heitler complication is irrelevant.

Our calculation [6] starts from a pole fit to Compton scattering data over a wide energy and angular range [11]. These data are described by the nucleon Born terms (including exchange) plus the s -channel resonance terms where a coherent summation over as many as 26 nucleon resonances is performed.

In [6] we have generalized this semi-empirical description to the case of outgoing massive, time-like photons; in this way we make sure that the calculations reproduce the data when the photon approaches the on-shell point. The coupling to the new longitudinal degree of freedom of the massive photon is determined by explicitly demanding current conservation and gauge invariance.

The analysis by Wada et al. involves momentum-dependent vertex factors for the photon-nucleon vertex. We interpret this dependence (on the three-momentum) as a half-off-shell dependence of the formfactors for a real photon; in this way we have effectively determined the half-off-shell behavior of the formfactors from experiment. In order to check the consequences of an additional VMD-like dependence on the photon momentum we then multiply the outgoing vertex factor by a VMD formfactor that peaks at the vector meson mass. This procedure assumes that the nucleon off-shell effects decouple from the photon off-shell effects on the formfactor.

The results of these calculations are shown in Figs. 4. The left part of Fig. 4 gives the dilepton invariant mass spectrum for forward emission angles of the dilepton (small opening angles of the pair with respect to the direction of the incoming photon momentum). It is evident that the spectrum is dominated over a wide range by the Bethe-Heitler contribution. Nevertheless the spectrum shows a shoulder-like structure in the vector meson mass

Figure 4: Dilepton invariant mass spectrum for $\gamma + p$ at 1.2 GeV for forward (left) and backward (right) emission angles of the dilepton pair (from [6]).

region, which is dominated by the resonance channels. For large opening angles, i.e. backward emission (right part of Fig. 4), the overall cross section is smaller, but the resonance structure is more pronounced; again the resonances contribute somewhat more to it than the nucleon Born graph. Thus, an experiment of this sort will determine a formfactor that is averaged over the nucleon and its excited states.

5 Conclusions

In this contribution I have discussed a novel approach to the electromagnetic formfactor of the nucleon in the timelike regime. I have shown that existing data on proton induced dilepton production on light nuclei seem to be in gross disagreement with predictions based on a naive VMD picture. Based on results of a microscopic model I have argued that this disagreement may be due to off-shell effects on the formfactors. I have also indicated that it may be difficult to disentangle the effects of the strong interaction and the electromagnetic interaction vertices in nucleon-nucleon collisions.

An experiment that would give direct access to the time-like electromagnetic formfactor without the strong interaction complications is Compton scattering into the time-like region. I have presented calculations and have shown that the dilepton spectra expected from such a reaction are quite sensitive to the electromagnetic formfactor.

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